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UTAH WINTER SEVERITY INDEX PHASE 1

Prepared For:

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UDOT RESEARCH & DEVELOPMENT REPORT ABSTRACT

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16. Abstract

UDOT's objective is to create a winter severity index (WSI) that will evaluate each storm and winter season's severity. Storm severity is a compilation of storm impacts and the relative difficulty of mitigating those impacts. Utah's complex terrain and varying statewide weather conditions make it a unique problem to evaluate a winter storm's impact on a regional or statewide scale. Very little prior work has focused on an area with terrain similar to Utah's and had similar goals. Phase I of this project summarizes previous WSI work and provides Utah-specific recommendations for going forward.

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LIST OF ABBREVIATIONS

UDOT	=	Utah Department of Transportation
DOT	=	Department of Transportation
WSI	=	Winter Severity Index
RWIS	=	Road Weather Information System
ESS	=	Environmental Sensing Station
FHWA	=	Federal Highway Administration
VAMS	=	Value Added Meteorology Service
SHRP	=	Strategic Highway Research Program
SSI	=	Storm Severity Index
WI	=	Winter Index
LWSS	=	Local Winter Storm Scale
INDOT	=	Indiana Department of Transportation
ITD	=	Idaho Transportation Department
RTMA	=	Real-Time Mesoscale Analysis

EXECUTIVE SUMMARY

Winter weather can be assessed by various measures of impact, whether to society or to agencies charged with mitigating the impacts of the weather. The Utah Department of Transportation Maintenance Division wishes to analyze the impact that winter storms have on their maintenance operations. The goal is to create a winter severity index (WSI) that distills weather impacts into a single index value. The WSI will be applied to individual storms and will be calculated at a high resolution, so as to capture Utah's many terrain-induced microclimates. The intended result of a WSI is the ability to analyze needed resource allocation among maintenance sheds, measure their performance, and, potentially, to forecast the allocation of resources prior to a weather event.

Many non-DOT studies relate winter severity to traffic operations or human intrinsic values. Though these do not focus on weather's impact on maintenance resource consumption, they lay a foundation useful for building a WSI from scratch. One recommendation was to go beyond theoretical assumptions of weather impact, and to involve expert opinion, such as in Qiu (2008) and McChullouch et al. (1996). These surveys asked snow and ice mitigation experts to assign values to different winter storm scenarios in order to properly weigh the impact of the individual storm elements.

A few other state Departments of Transportation have developed severity indices for snow and ice mitigation. The indices they use range from direct copies of a previously-developed index (SHRP Index, Boselly et al. 1993) to an index of their own development. Some calculated their index on a season-by-season basis, and others storm-by-storm. The table in Appendix A summarizes previous studies reviewed here.

Utah's statewide climate is unique to other states, but not only because of terrain influences. For instance, Utah rarely, if ever, experiences freezing rain and many indices include freezing rain as a major contributor to winter impacts. In Utah, an ice term may be better described by frost formation or refreezing of melted snow. Idaho Transportation Department (ITD) directly measured road surface state at its road weather information system environmental sensing stations (RWIS ESS) and included it in its calculations. However, UDOT's goal is to interpolate data between RWIS stations, thus filling in its many data gaps, and representing microclimatic influences on weather severity.

Large data gaps and microclimatic variability necessitate high resolution data analysis techniques. Utah precipitation is only sparsely measured by 2 radars with blockage and overshooting problems, creating large radar gaps through the middle of the state. Many of UDOT's 73 RWIS ESS are strategically placed to fill data voids, but because they are only point measurements, a spatial representation of surface weather is still missing. Mesoscale analysis tools and mobile weather sensing should be investigated as ways to close data gaps and spatially represent surface weather.

Phase II of this project will develop a Utah-specific, storm-by-storm WSI. One recommendation for Phase II is to consider Utah's unique weather. Complex terrain and Utah's statewide climate are responsible for weather nuances that create their own impacts. Employing expert opinion, from forecasters to field personnel, will be necessary for this consideration. Another recommendation is to utilize techniques to fill in Utah's many data gaps. Mesoscale analysis tools and mobile weather sensing will provide the higher resolution weather data necessary to calculate WSI across the entire state, even in regions of complex terrain.

1.0 INTRODUCTION

Weather impact can be evaluated by distilling individual storm elements into a single severity index value. A weather-related severity index includes the storm elements that contribute most to a storm's impact, and is defined by the type of impact it has on society or an organization. For a transportation agency, one can compare impacts to the traveling public or to the agency's traffic operations or maintenance divisions. This study focuses on winter impacts to the Utah Department of Transportation (UDOT) Maintenance Division.

Identifying the ways in which the severity of winter weather can affect snow and ice mitigation is a key advantage when preparing for a winter season or reviewing a previous season. Thus, in order to determine the performance of an agency in dealing with a particular winter storm it is critical that the severity of the storm be quantified in some way (Qiu, 2008). It may also help to determine the distribution of resources among DOT sheds in varying geographic locations. The ability to do so can be extremely beneficial in a large state with variable terrain, such as Utah (see figure 1).

Topography plays a notable role in Utah's weather and climate. Utah has areas of low desert and high plateaus, mountain ranges with peaks reaching over 12,000 feet, and a number of lakes dotting the landscape. State-maintained roadways cross 5850 centerline miles of this complex terrain. Because of the diverse topography, weather conditions across the state vary widely, and can even change significantly over a couple of miles in many areas. These microclimates require special consideration during the evaluation of winter weather. This paper will highlight some of these considerations and will make recommendations for the formulation of a severity index specific to Utah.

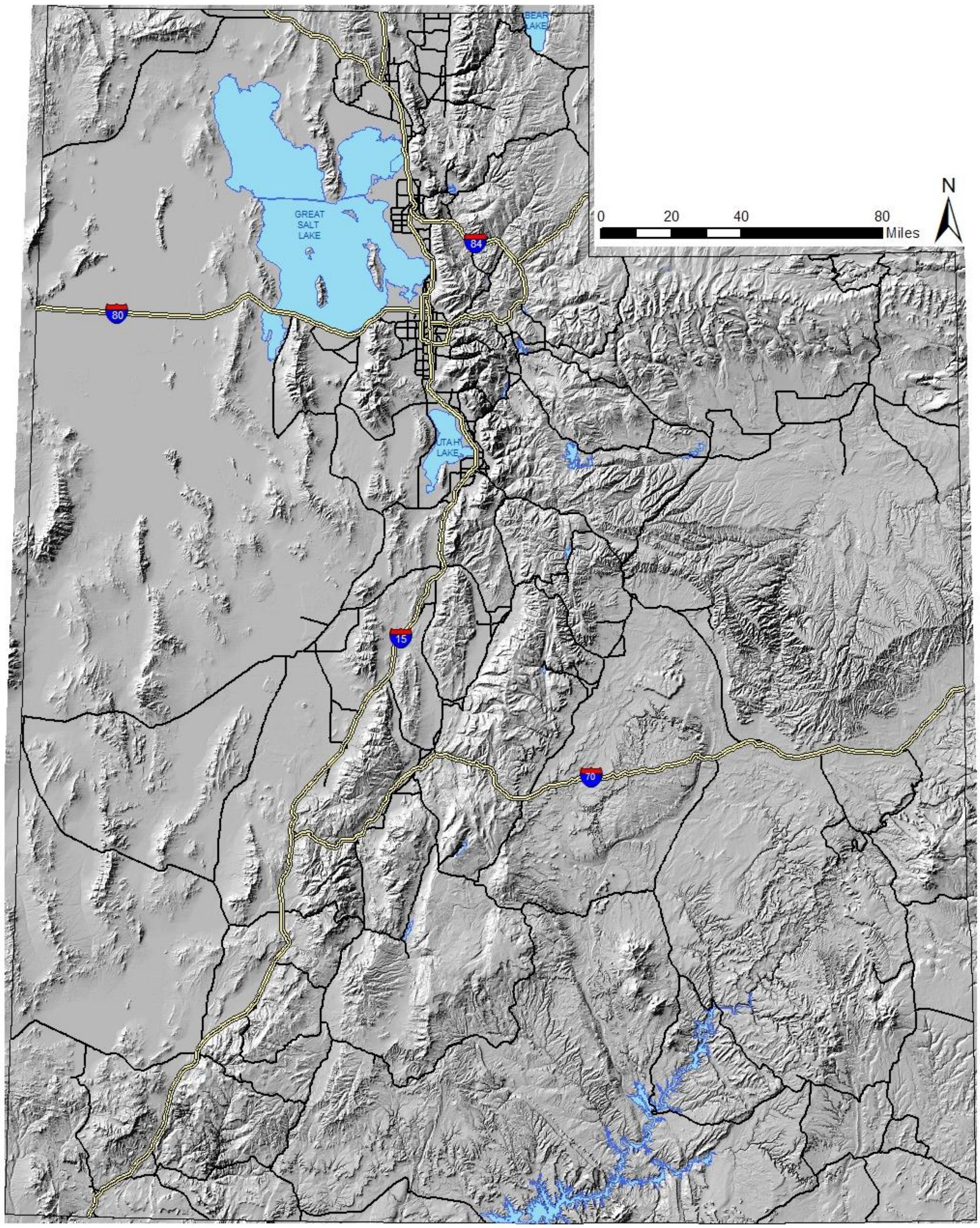

Figure 1. Map of the state of Utah showing UDOT roads through complex terrain and nearby lakes

A number of storm elements influence road conditions. Precipitation and road surface temperature are among the most influential. Considerations for precipitation should include type, rate, quantity and duration of precipitation falling onto a road surface, and how these aspects change with elevation. The temperature of the road surface is important because it controls the formation of bonds between fallen precipitation and the road, as well as the effectiveness of chemical treatments. Road temperature is largely a function of air temperature, soil temperature and exposure to solar radiation or precipitation, and therefore it will vary in time and space (Ketcham et al., 1996). Great variations of road temperature over short distances can occur in mountainous terrain due to colder temperatures at higher elevations, areas of shading from terrain features and cold air pooling in valley bottoms. Low sun angles during winter months and cloud cover will also reduce solar radiation absorption, but on a more regional scale than terrain features. It is also important to consider trends in the temperature of the pavement before, during and after precipitation events, as critical temperature thresholds may be reached or surpassed as the road temperature trends up or down. Other important environmental factors to consider for road conditions are humidity of the air and wind speed and direction, especially during and after snowfall. As with temperature and precipitation, moisture and wind can vary greatly in complex terrain.

Phase I of this project reviews other efforts and builds the foundation for UDOT to create its own severity index for snow and ice mitigation. Section 2 of this document provides background in snow and ice mitigation specific to Utah. Section 3 reviews previous work, providing examples of indices used for traffic, societal and maintenance impacts, and takes a closer look at how to weigh storm elements relative to one another as contributors to a storm's overall impact. Section 4 reviews indices used by other state DOTs. Appendix A contains a summary of the indices reviewed in this document. Herein, UDOT's index will be referred to as the winter severity index (WSI), but other authors refer to a storm severity index (SSI), winter index (WI), Local Winter Storm Scale (LWSS), etc., each of which pertain to the same process of distilling storm impacts into a single value. It should be noted that some severity indices are calculated over an entire season, and some from storm to storm. UDOT's goal is to calculate WSI on a storm-by-storm basis initially, and then to accumulate the impacts over a season as a whole. Sections 5 and 6 detail the unique weather (Section 5) and large gaps in surface weather data (Section 6) that make it a unique challenge to evaluate weather impacts across the state of

Utah. Taking those considerations into account, Section 7 presents recommendations for Phase II of this project: the development of UDOT's WSI.

2.0 SNOW AND ICE MITIGATION IN UTAH

UDOT maintenance personnel rely heavily on weather observations, forecasts and road weather information systems (RWIS) to determine their approach to snow and ice mitigation. The "Manual of Practice for an Effective Anti-Icing Program" (Ketcham et al. 1996) contends that, "the decision whether or not to initiate a [road] treatment, when to start and what treatment to apply, can only be made if good weather information is available." This is where RWIS weather stations and a value added meteorological services (VAMS) prove their value. VAMS provide forecasts that are specific and customized towards the parameters and road segments in which shed personnel are interested. Meanwhile, RWIS sites contain sensors that monitor road temperature, road condition, wind speed and direction, air temperature, relative humidity, precipitation presence, solar radiation and soil temperature. The ability to view weather conditions at specific locations along stretches of highway is a key advantage in decision making. Additionally, proactive rather than reactive mitigation can reduce the resources needed to fight a storm.

Snow and ice mitigation begins with treating the roads with a chemical agent that lowers the temperature at which ice will develop. This process is executed during all phases of the storm (pre-storm, during-storm and post-storm). An anti-icing chemical must form a solution in water in order to depress the freezing point, but the solubility of these chemicals varies with temperature; the lower the temperature, the less soluble the solution will be (Ketcham et al., 1996). Therefore, in order for the chemical to be effective, personnel must know the road temperature prior to treatment, and the road temperature at which precipitation will freeze after it forms a solution with the chemical.

Ketcham et al. (1996) present specifics on how treatment varies as a function of temperature. The tables in Appendix B may be referred to for greater detail. Note that at road temperatures above freezing, no chemical treatment, only plowing, is required. Below 15 °F, chemicals become ineffective and the recommended actions are plowing as needed and applying abrasives. Between 15 and 32 °F, however, treatment becomes variable based upon temperature and precipitation intensity. As temperatures drop within this range, chemical application increases and chemical type changes based on temperature. As precipitation intensity increases, application rates increase further and plowing occurs as much as possible. However, minute changes in temperature can result in significant impacts to treatment, and these relatively small variations in storm parameters should be considered in a severity index calculation.

3.0 PREVIOUS STUDIES

3.1 The Winter Severity Index as a Function of Traffic Impact

There are variations of severity indices that have served disparate purposes for the agencies that created them. Few of the projects completed by non-DOT organizations relate resource use to the severity of winter storms. Only a couple even suggest creating an index for each individual storm for the purpose of comparing storms.

In many past studies, the motivation for creating a WSI was largely due to accident reports or societal impacts. “Performance Measurement for Highway Winter Maintenance Operations” (Qiu 2008) is one such study. While the ultimate objective of Qiu’s study is to relate mitigation efficiency to traffic and accidents, in the process, Qiu goes through the calculation of a storm severity index for snow and ice mitigation. Publications such as “Development of a Roadway Weather Severity Index” (Strong et al., 2005) and “The Local Winter Storm Scale” (Cerruti and Decker, 2011) focus on relating weather severity directly to traffic operations and societal impacts. However, these reports provide a foundation for creating a WSI that serves a maintenance resource management purpose.

For instance, Qiu’s research defines a storm using a flow chart (Fig. 2) that considers different features of storms and their importance. The flow chart describes a storm in terms of six variables. These variables are storm type, in-storm temperature, early storm behavior, in-storm wind conditions, post-storm temperature and post-storm wind conditions. These variables were weighted based on their mitigation disruption capabilities (Table 1). First approximations of these values (those not in parentheses in Table 1) were obtained by Qiu from the Federal

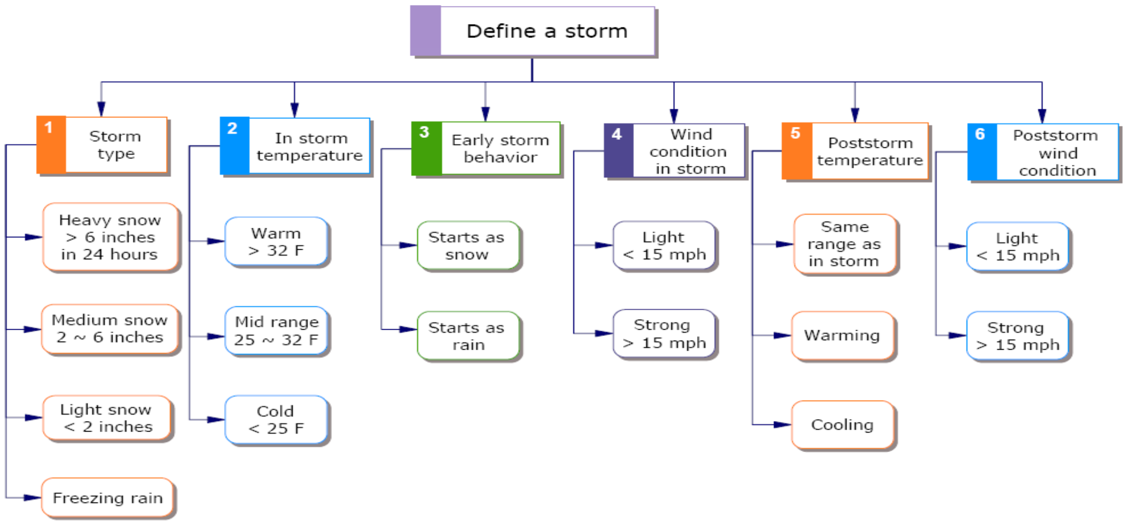

Figure 2. Flow chart defining storm feature thresholds (Qiu 2008)

Highway Administration (FHWA) Manual of Practice of Recommended Treatments (1999). Qiu then modified the values using a survey conducted among winter maintenance supervisors (Table 2). This survey asked the supervisors to rank storm scenarios by difficulty of keeping roads clear during each event, the most difficult being a ten and the least difficult being a one. The results of this survey, seen in Table 3, bottom row, are compared to the initial values (upper row) that were

Table 1. Weighted Scores for Each Storm Index Factor, Qiu (2008)

Storm Type	Freezing rain 0.4 (0.72)	Light Snow 0.35	Medium Snow 0.65 (0.52)	Heavy Snow 1
Storm Temperature	Warm 0.25	Mid Range 0.6 (0.4)	Cold 1	
Wind Conditions in Storm	Light 1	Strong 1.2		
Early Storm Behavior	Starts as Snow 0	Starts as Rain 0.1		
Post Storm Temperature	Same 0	Warming -0.087	Cooling 0.15	
Post Storm Wind Conditions	Light 0	Strong 0.15 (0.25)		

Table 2. Storm Scenarios from Qiu (2008)

A: A storm with freezing rain and temperatures in the warm-range (above 33°F) that starts as rain. Winds in the storm are strong (over15mph). After the storm, winds become light and temperatures warm up.

B: A storm with heavy snow (above 6 inches) and temperatures in the midrange (25°F to 32°F) that starts as snow. Winds in the storm are strong (over 15 mph). After the storm, winds become light and temperatures cool down.

C: A storm with heavy snow (above 6 inches) and temperatures in the warm-range (above 33°F) that starts as rain. Winds in the storm are light (less than 15 mph). After the storm, winds become strong and temperatures cool down.

D: A storm with heavy snow (above 6 inches) and temperatures in the warm-range (above 33°F) that starts as snow. Winds in the storm are light (less than 15 mph). After the storm, winds become strong and temperatures cool down.

E: A storm with light snow (up to 2 inches) and temperatures in the warm range (above 33°F) that starts as snow. Winds in the storm are light (less than 15 mph). After the storm, winds remain light and temperatures warm up.

F: A storm with freezing rain and temperatures in the cold-range (15°F to 25°F) that starts as rain. Winds in the storm are light (less than 15 mph). After the storm, winds remain light and temperatures remain cold.

G: A storm with medium snow (2 inches to 6 inches) and temperatures in the midrange (25°F to 32°F) that starts as snow. Winds in the storm are light (less than 15 mph). After the storm, winds become strong and temperatures warm up.

Table 3. Average Expert Rank vs. Storm Index Rank from Qiu (2008)

Storm scenario	E	A	I	H	G	F	D	C	B	J
Storm Index rank	1	2	3	4	5	6	7	8	9	10
Avg. Expert rank	1	4	2	3	5	9	7	8	6	10

assigned to each index factor listed in Table 1. The modified weighted scores are shown in parentheses in Table 1. The difference between the initial and modified values highlights the need for expert opinion in understanding the severity of storm impacts.

Qiu created a storm severity index (SSI) using the revised ranks and an equation derived from "Road Weather Information Systems Volume 1: Research Report" (Boselly et al., 1993). The final equation is:

$$SSI = \left[\frac{1}{b} * \left[\left(ST * Ti * Wi \right) + Bi + Tp + Wp - a \right] \right]^{0.5} \quad (1)$$

where:

SSI: Storm severity index;

ST: Storm type;

Ti: In storm road surface temperature;

Wi: In storm wind condition;

Bi: Early storm behavior;

Tp: Post storm temperature;

Wp: Post storm wind condition;

a,b: Parameters to normalize storm severity index from 0 to 1.

Numerical values for *ST, Wi, Bi* and *Bp* come from Table 1. The result, *SSI*, is the calculated severity index for mitigation efforts. Qiu then used the result of Equation 1 as a variable in another equation relating traffic accident frequency to weather conditions.

"Development of a Roadway Weather Severity Index" (Strong et al. 2005) also focused on traffic impacts, but in the mountainous states of Montana, Oregon and California. This publication introduced the concept of normalizing results to the type of climate zone from which the data come. The authors assigned locations to one of three climate zones: mountain, valley or plain. They defined a mountain zone as an area where there is significant decrease in altitude in any direction within 5-10 miles from the road. A location was classified as a valley if any minor increase in altitude was observed within 5-10 miles of the road, on either side of the road. This zone included mountain front areas as well. If there was no significant change in elevation within 5-10 miles of a location, that area was classified as a plain (Strong et al. 2005). The authors did not define the terms, significant or minor in the text. The climate zones in each state had separate equations for relating accident rates to weather conditions. Montana's geographic and climatic features are most similar to Utah; therefore, equations developed for Montana are shown below (Equations 2-4). These formulas estimate traffic accident rates in relation to weather conditions in their respective zones. The equations for Oregon and California are found in Appendix C.

Montana Mountain Zone:

$$AccRate = 0.88376 + 0.44804 S_{freq} - 0.26409 F \tag{2}$$

Montana Valley Zone:

$$AccRate = 1.31229 - 0.02211 T_{max} + 0.02771 T_{dp} + 14.0862 S \tag{3}$$

Montana Plains Zone:

$$AccRate = 1.19234 - 0.02153 T_{max} + 0.02771 T_{dp} + 14.0862 S \tag{4}$$

where:

- $AccRate$ = Accident Rate
- S_{freq} = Frequency of snowfall events;
- F = Average daily likelihood of frost;
- T_{max} = Average daily maximum temperature;
- T_{min} = Average daily minimum temperature;
- T_{dp} = Dew point temperature;
- S = Average daily snowfall;
- $T_{<freeze}$ = Number of days with temperature below freezing;

W_{avg} = Average daily wind speed;

N_{snow} = Number of days per month with snowfall.

3.2 SHRP Winter Index

The Strategic Highway Research Program (SHRP) studies, "Road Weather Information Systems: Volumes 1 and 2" (Boselly et al.) were completed in 1993, in part, as a means to assign a winter seasonal severity index to any location. According to Boselly and Ernst, "a new winter index is expected to be an objective indication of winter severity and reflect the importance of winter maintenance, and to have general application in many countries, i.e. only a few general or common parameters are to be employed." The SHRP winter index (WI) restricts its parameters to specifically account for temperature, amount of snowfall and the frequency of ground frost. Due to this generalization of parameters, many areas require a modified version of the SHRP WI. The equation for the SHRP index is:

$$WI = a\sqrt{TI} + b\ln\left(\frac{S}{10}+1\right) + c\sqrt{\left(\frac{N}{R+10}\right)} + d \qquad (5)$$

The *a*, *b* and *c* terms account for temperature, snowfall and frost respectively, *d* is a corrective term, and TI, S, N and R are defined in Table 4. According to the SHRP study, "the coefficients for [Equation 5] are derived by taking into account the critically significant level of each parameter to winter maintenance cost (1.87 for TI, 16.5 for S, and 1 for N), and solving a set of simple equations." The resulting coefficients are (Boselly et al., 1993):

a = -25.58;

b = -35.68;

c = -99.5;

d = 50.0.

This yields the final equation for the calculation of WI over an entire season:

$$WI = -25.58\sqrt{TI} - 35.68\ln\left(\frac{S}{10}+1\right) - 99.5\sqrt{\left(\frac{N}{R+10}\right)} + 50 \qquad (6)$$

Table 4. Definitions of Variables in SHRP Index

Temperature Index (TI)	TI = 0 if the minimum air temperature is above 32°F; TI = 1 if the maximum temperature is above freezing while the minimum temperature is below 32°F; and TI = 2 if the maximum temperature is at or below 32°F. The average daily value is used.
Snowfall (S)	Mean daily values in millimeters (the number of days with snowfall was also considered but did not improve the index).
Number of Air Frosts (N)	Mean daily values of number of days with minimum air temperature at or below32°F ($0 \leq N \leq 1$).
Temperature Range (R)	The value of mean monthly maximum air temperature minus mean monthly minimum temperature in °C.

3.3 Storm Element Weighting

Weather conditions affect snow and ice mitigation differently, and some storm elements generate more of an impact than others. Therefore, these variables should be weighted differently to account for their different magnitudes of impact. For example, precipitation rate tends to impact road conditions more than wind speed, but determining how much more, requires the use of carefully tested weighting constants. Although their study focused on societal rather than agency impacts, Cerutti and Decker (2011) show how to develop weighting constants in their article, "The Local Winter Storm Scale." The local winter storm scale (LWSS) is defined by:

$$LWSS = \sum_k w(k)\sigma_k \qquad (7)$$

where, w is the weighting function; σ is the storm element score; and k is an integer such that $1 <= k <= 5$, indicating the following variables (storm element scores) in order: maximum sustained winds, maximum wind gust, storm snow total accumulation, storm total ice accretion, and minimum visibility. Storm element scores are determined by using linear piecewise interpolation and the data shown here in Table 5 (Cerutti and Decker, 2011). A justification for the breakpoints used in Table 5 is available in Table 6. Many of these breakpoints correspond with National Weather Service advisory, watch and warning criteria. According to Cerruti and Decker, “precipitation rates would be included in LWSS; however, the lack of reliable hourly precipitation data from surface observations when snow is present prevents inclusion of these data.”

From Table 5, a formula to solve for σ is derived:

$$\sigma_k = \frac{s - c_l}{c_u - c_l} + C \tag{8}$$

where s is the storm element’s observed value; c_l and c_u are the categorical lower and upper

Table 5. Definition of Storm Element Scores for Weather Elements from Cerruti and Decker (2011)

Storm element score (LWSS descriptor)	Sustained wind kt (m s^{-1})	Wind gust kt (m s^{-1})	Snow in. (cm)	Ice in. (cm)	Visibility mi (km)
Weighting function	20%	15%	50%	30%	15%
0 (nuisance)	0 (0)	0 (0)	0 (0)	0 (0)	10 (16.1)
1 (moderate)	7 (3.6)	13 (6.7)	2 (5.1)	T (T)	3 (4.8)
2 (significant)	11 (5.7)	17 (8.7)	4 (10.2)	0.1 (0.3)	1 (1.6)
3 (major)	17 (8.7)	22 (11.3)	10 (25.4)	0.25 (0.6)	0.5 (0.8)
4 (crippling)	22 (11.3)	30 (15.4)	15 (38.1)	0.5 (1.3)	0.25 (0.4)
5 (extreme)	27 (13.9)	41 (21.1)	20 (50.8)	0.75 (2.5)	0.125 (0.2)
6 (catastrophic)	34 (17.5)	48 (24.7)	25 (63.5)	1 (5.1)	0 (0)

Table 6. Justification for Breakpoints from Cerruti and Decker (2011)

Storm element score	Sustained wind	Wind gust	Snow	Ice	Visibility
0	Less than gentle breeze	Less than Rooney (1967) minimum disruption	Below minimum requirement for winter storm warning in all of eastern region	Below freezing rain advisory criteria	Above minimum requirement for instrument flight rules
1	Gentle to moderate breeze	Minimum Rooney (1967) disruption to fresh breeze	Meets minimum winter storm warning criteria to first isopleth of snowfall used in NESIS calculations	Meets freezing rain advisory criteria in the eastern region	Typical values for instrument flight rules
2	Moderate to fresh breeze	Fresh to strong breeze	First to second isopleths of snowfall in NESIS	Almost meets minimum ice storm warning criteria in the eastern region	Between instrument flight rules and very low instrument flight rules
3	Fresh to strong breeze	Strong breeze to NWS blizzard criteria	Second isopleth for snowfall in NESIS; exceeds 24-h criteria for winter storm warning in all of eastern region	Exceeds ice storm warning criteria for much of the eastern region	Very low instrument flight rules; typical criteria for closing an airport; blizzard criteria nearly met
4	Strong breeze to near gale	NWS blizzard criteria met	Linear extrapolation between NESIS values	Exceeds ice storm warning criteria for all of the eastern region	Requirements for blizzard visibility criteria met
5	NWS wind advisory	NWS high wind warning criteria met	Third isopleth in NESIS	Convenient benchmark	Near whiteout
6	Gale force winds; NWS high wind warning	Storm-force winds	Linear extrapolation between NESIS values	Convenient benchmark	Whiteout

bounds, respectively, of that value and C is the appropriate category number. Knowing s, one can use Table 5 to determine c_l, c_u, and C. For example, when solving for σ_k where k = 1 (sustained wind), if a storm's sustained wind speed (s) is 24 kts, from the sustained wind column of Table 5, c_l = 22 kts, c_u = 27 kts and C = 4. Inserting this data into Equation 8 results in σ_1 = 4.4. Later, σ_1 will be multiplied by the weighting factor, w, which is responsible for adjusting the value of σ to account for its percentage of perceived impact. After finding the weighted score of each element, they are summed using Equation 7 to achieve a final LWSS value.

Cerruti and Decker (2011) used storm element weights from Qiu (2008) and Changnon (2007), as shown in Table 7, to derive the weighting functions for each winter storm element. Changnon (2007) relates the total cost of storm damage to the severity of winter storms.

Table 7. Data Used to Derive LWSS Weighting Function from Cerruti and Decker (2011)

Qui (2008)			Changnon (2007)		
Variable	Coef.	Normalized	Variable	Count*	Normalized
In-storm wind (>15 mph) WG	1.20	0.38	Wind WGV	149	0.42
Poststorm wind (>15 mph) V	0.25	0.08			
Heavy snow	1.00	0.32	Heavy snow	136.5	0.39
Freezing rain	0.72	0.23	Freezing rain	65.5	0.19

*Modified from the Changnon (2007) analysis to partition the snow and freezing rain cases equally between heavy snow and freezing rain.

Because neither study separated wind, wind gust and visibility, it was assumed that a combination of these elements fell within one or two elements in each study. In Qiu's report, it is assumed post-storm winds can be used as a proxy for a visibility coefficient because most post-storm roadway maintenance problems are the result of blowing snow (Cerruti and Decker, 2011). However, Qiu does not specify between sustained winds and wind gusts, therefore the in-storm wind normalized coefficient is divided equally between wind and wind gust. In Changnon's review, it is assumed that the wind variable encompasses sustained winds, wind gusts and visibility. Therefore, its normalized coefficient value is divided equally by three to yield a value for the three different storm elements. The results of this work are seen in Table 8. Cerruti and Decker then performed a multiple linear regression using 15 winters worth of data from Newark Liberty International Airport. This regression produced the normalized coefficient in Table 8. Finally, to ensure that scores associated with ice storms were not artificially low due to a lack of snow accumulation, ice accretion was increased to 30% and the remaining storm elements were decreased proportionally by 5% each. The authors do not go into significant detail about how they arrived at the initial LWSS weight or the final LWSS weight, in Table 8. It appears some rounding was done for simplification purposes as well. An example of how LWSS is calculated for a storm is provided in Table 9.

Table 8. Calculations of Storm Element Score Weights from Cerruti and Decker (2011)

Storm element	Qui (2008)	Changnon (2007)	Normalized coef.	Initial LWSS wt*	Final LWSS wt
Wind	0.19	0.14	0.15	0.154	0.20
Gust	0.19	0.14	0.13	0.147	0.15
Snowfall	0.32	0.39	0.55	0.404	0.50
Freezing rain	0.23	0.19	0.17	0.189	0.30
Visibility	0.08	0.14	N/A	0.106	0.15

*Initial weights are calculated from a normalized average of all previous data for each storm element.

Table 9. Example of How LWSS is Calculated from Cerruti and Decker (2011)

Variable	Observed value	σ	$w\sigma$
Sustained wind	24 kt (12 m s^{-1})	4.4	0.88
Wind gust	33 kt (17 m s^{-1})	4.27	0.64
Snowfall	21.3 in. (54.1 cm)	5.26	2.63
Icing	None	0.00	0.00
Visibility	0 mi (0 km)	6.00	0.90
LWSS = 5.05 (extreme)			

4.0 WINTER SEVERITY INDICES USED BY OTHER STATE DEPARTMENTS OF TRANSPORTATION

Several other states and one Canadian province are reviewed here as having implemented their own variations of winter severity indices for transportation maintenance operations. Those that have accomplished this, have done so in one of three ways: (1) they directly utilized the index found in the SHRP study, "Road Weather Information Systems Volume 1: Research Report," (2) they modified the SHRP index in some way to meet their requirements, or (3) they created an entirely original index. The known states that directly employ the SHRP index are Kansas and Minnesota. The states that have modified the index or created their own include Wisconsin, Indiana, Iowa, Idaho, Massachusetts and Ontario. However, the Massachusetts index is currently a work in progress (personal correspondence, Paul Brown, Massachusetts DOT) and is not reviewed here.

4.1 Wisconsin DOT

Wisconsin DOT's winter index is calculated on a seasonal basis. It accounts for the number of snow events, freezing rain events, total snow accumulation and total storm duration over the course of an entire season. It was decided that another factor, incidents, would be included in their index. Incidents include drifting of snow, cleanup and frost mitigation. Other criteria such as wind speed and direction, and pavement temperature were considered important, but were not used due to a lack of reliable information. This index was applied to each winter season in every county. It should be noted that the severity index was not created to be utilized on a storm by storm basis, but on a seasonal basis. Wisconsin DOT's goal for creating a winter index was to relate winter severity to resource use. Therefore, estimates of chemical prices and shed crew pay were also considered in this study.

Using information submitted by all of the counties, the following methodology was used:

a. Add up the totals in each of the 5 categories listed in Table 10 for each of the last six winters and all winters combined.

b. Add up the total salt and man hours used for each winter and all winters combined. For salt usage, the State Furnished Materials (SFM) report was used instead of storm report data as the SFM was thought to be more reliable.

c. Develop correlation coefficients between each of the five weather factors and the two cost factors and a total cost factor to see which weather factors correlated most strongly to which cost factors. To calculate this total cost factor, the following formula was used:

$$TotalCost = \$30 \times TonsOfSalt + \$50 \times TotalHoursUsed \qquad (9)$$

where $30 is an estimate of the average cost per ton of salt and $50 is an estimate of the hourly labor and equipment rate.

Table 10. Correlation Coefficients of Variables in Wisconsin DOT's WSI

Weather Factor	Correlation Coefficient	Weighting Factor
Number of Snow Events (SE)	0.490	10
Total Storm Duration (DUR)	0.462	9.4
Number of Incidents (INC)	0.449	9.2
Total Snow Amount (AMT)	0.415	8.5
Number of Freezing Rain Events (FR)	0.291	5.9

d. Assign weights of importance to the five weather categories. These weights were calculated by assigning the highest correlated criteria a value of ten and then assigning a weight to the others based on the ratio of the respective correlation coefficients. The correlation coefficients for the winters of 1992-93 through 1997-98 are listed in Table 10.

e. In each of the five categories, compare each county's value to that of the county with the maximum value in the category during the five-year period. These maximum values were:

Snow Events: 63

Freezing Rain Events: 21

Snow Amount: 314

Duration: 1125

Incidents: 55

f. Divide each county's value in a particular category by the maximum value to assign a numerical percentage to that value. This was done for each individual winter and for a five-winter average.

g. After multiplying the percentages by the weighting factors for each category add the five categories together. This yields the following formula:

$$RawIndex = 10\times\frac{SE}{63} + 5.9\times\frac{FR}{21} + 8.5\times\frac{AMT}{314} + 9.4\times\frac{DUR}{1125} + 9.2\times\frac{INC}{50} \quad (10)$$

According to the Wisconsin DOT Technical Document, a couple of problems arose from the methodology. First, not every county reacts the same way to a particular situation. Therefore, given the exact same conditions, one county may submit a storm report while another does not, simply because one county called out its crews and the other did not. Another problem arose when crews reported the storm type. Many storms produce both snow and freezing rain. In order to avoid cataloging one storm as two different events in these situations, they had to determine the predominant precipitation type during an event. A storm that brought more than one inch of snow was categorized as a snow event and a storm that brought an inch or less of snow, accompanied by freezing rain, was considered a freezing rain event (Technical Document, Wisconsin DOT).

4.2 Indiana DOT

The Indiana Department of Transportation (INDOT) uses a winter index to compare the efforts of snow and ice removal between different climatic zones, to compare differing winter seasons, and also to provide a quantitative method for determining what relationships exist between various weather events and mitigation. Therefore, INDOT decided to develop its own index, using the total cost/mile as the dependent function in the equation. Details in this section were obtained from a Winter Severity Index Study performed within INDOT (McChullouch et al. 2004).

The state of Indiana was divided into four distinct climate zones. The southernmost zone of the state experiences a shorter, milder winter, while the central zone experiences a colder and snowier winter than the south. The northern section of the state observes much colder winter temperatures and is split into two separate climate zones. The western zone experiences lake effect snow events from Lake Michigan.

A survey was conducted with field crews and employees involved in snow and ice removal to obtain the level of difficulty for mitigating certain weather conditions. The group identified frost, freezing rain, snow events and snow drifting as the four weather factors with the most influence. Additionally, the survey asked to distribute 100 points between the four main weather events to determine how much weight to assign each event, producing the following equation:

$$WI = a(Frost\ Day) + b(Freezing\ Rain) + c(Snow\ Event) + d(Drift\ Day) \quad (11)$$

Where:

a = 0.06;

b = 0.29;

c = 0.38;

d = 0.27.

A snow event is affected by the amount of snow, the duration of the event and the temperature during the event. These factors, as well as the definition of a snow event are available in Table 11. Substituting the variables from Table 11 into Equation 11 yields the new formula for WI:

$$WI = 100 * \left(0.06 * (FrD) + 0.29 * (RfD) + 0.38 * (DrD) + 0.27 * (SnD) * \frac{In}{AvT}\right) \quad (12)$$

The formula was tested at each location and it was determined that it was too difficult to validate. It was felt that there was too much bias involved in the survey responses. For example, some locations use pre-treating to prevent frost and do not consider it an important factor in winter weather mitigation, while others respond to frost call-outs in the middle of the night, giving it a higher priority. Therefore, a more statistical approach was taken.

Table 11. Weather Condition Definitions for Indiana DOT's SI

Events	Symbols	Definitions
Frost	FrD	Number of days with minimum temperature ≤ 32°F and a minimum dew point ≤ 32°F.
Freezing Rain	RfD	Number of days with freezing rain and/or drizzle and minimum temperature ≤ 32°F.
Drifting	DrD	Number of days with wind speeds > 15 mph and snow on the ground or during a snow event
Snow	(SnD)*In/AvT	Number of days with minimum temperature ≤ 32°F times the snowfall intensity divided by the average temperature during the event.

Using lane mile cost as the controlling variable, this problem was solved by using a multiple regression analysis, accounting for the multiple weather variables. SAS, an interactive and batch programming environment that provides modules for basic data analysis, statistics and report writing, was used to perform the multiple regression analysis. As a result, an equation was developed for each region, as well as a statewide formula, Equation 13.

$$WI = 0.71839 * Frost + 16.87634 * Freezing\_Rain + 12.90112 * Drifting - 0.32281 * Snow + 25.72981 * Snow\_Depth + 3.23541 * Hour - 2.80668 * Avg\_Temp \tag{13}$$

It was also determined that the correlation between cost per lane mile and the WI increased when more weather variables were added. Therefore, snow depth, storm intensity (duration) and average temperature were added to the formula. The equations for each of the four individual climate regions are included in Appendix D.

4.3 Iowa DOT

Iowa DOT's winter index assigns a higher score to locations that report a longer duration event, more frequent events and more snowfall. It is a seasonal analysis. According to Iowa DOT's research document (Explanation of Index 3), "the duration and frequency of the different events are normalized by the Iowa expected extreme for each event, then scaled by an 'importance' factor." They also account for colder pavement temperatures and snow wetness consistency resulting in higher index scores. However, whether or not snow is dry or wet was based on the subjective opinion of the maintenance crews. Iowa uses the following formula:

$$
\begin{aligned}
Index3 = {} & \left(\frac{10}{57}\right) * \left(\#WetSnowEvents + \#DrySnowEvents\right) + \left(\frac{5.9}{9.0}\right) * \#FreezRainEvents + \left(\frac{8.5}{58}\right) * \\
& SnowIn + \left(\frac{9.4}{1125}\right) * \left(HrWetSn + HrDrySn + HrMixP + HrFreezRn + HrBlSn + HrSleet\right) - .25 * \\
& \left(wsnind + mpind + frind + slind\right) + .5 * \left(dsnind + bsnind\right)
\end{aligned} \tag{14}
$$

Where:

#WetSnowEvents = Number of wet snow events;

#DrySnowEvents = Number of dry snow events;

#FreezRainEvents = Number of freezing rain events,

SnowIn = Snowfall in inches;

HrWestSn = Hours of wet snow;

HrDrySn = Hours of dry snow;

HrMixP = Hours of mixed precipitation;

HrFreezRn = Hours of freezing rain;

HrBlSn = Hours of blowing snow;

HrSleet = Hours of sleet;

wsnind = Average of lowest temperatures during wet snow events - 29.6;

mpind = Average of lowest temperatures during mixed precipitation events – 30.22;

frind = Average of lowest temperatures during freezing rain events – 26.42;

slind = Average of lowest temperatures during sleet events – 29.52;

dsnind = 0.069*(average of lowest temperatures during dry snow events – 20)^2;

bsnind = 0.069*(average of lowest temperatures during blowing snow events – 20)^2.

By considering the duration, rather than solely the number of occurrences of each winter variable, Iowa DOT's winter index assigns more importance to time as a variable than other studies have.

4.4 Idaho Transportation Department

Of the states that have winter indices, the state of Idaho is the most similar to Utah in terms of climate and geography. It is also the only state reviewed here that calculates its index on a storm-by-storm basis and includes road conditions in its formula. Idaho Transportation Department (ITD) possesses an RWIS network composed of 85 environmental sensing stations (ESS). 56 of those ESS are "performance measure ready," meaning they are equipped with Vaisala DST-111 and DSC-111 non-invasive road sensors, and are used to calculate storm severity for performance measurement purposes (personal correspondence, Steve Spoor, ITD). The DST-111 monitors the road temperature while the DSC-111 analyzes road surface state. The DSC-111 is capable of reporting the type of precipitation accumulating on the road, the depth of the accumulated precipitation and the coefficient of friction on the surface.

ITD's storm severity index observes maximum wind speed, maximum surface precipitation and minimum pavement temperature in its formula:

$$Severity = W + S + \left(300 / T \right) \tag{15}$$

where

W = Maximum wind speed

S = Maximum surface precipitation water layer

T = Minimum pavement temperature

The severity is then divided into the ice-up time, which is the duration of time that the DSC-111 measures a coefficient of friction that falls below .60 for more than half of an hour and then rises above .60 for two consecutive hours. This results in the performance index:

$$Performance\ Index = \left(\frac{IceUp\ Time}{Severity} \right) \tag{16}$$

The performance index does not directly portray how well the maintenance crews performed. It relates the amount of time that ice exists on the road to the severity of a storm. This value can be influenced by temperatures being too cold or too warm for effective deicing treatment, duration of storm events, poor treatment response or a combination of the three (personal correspondence, Dennis Jensen, ITD).

4.5 Ontario Ministry of Transportation

The Ontario Ministry of Transportation (MOT) modified the SHRP index to include freezing rain instead of frost, as freezing rain has a relatively large impact on maintenance operations in the province. Equation 17 shows Ontario MOT's calculation of the winter index (compare to Equation 5).

$$WI = a(TI)^{0.5} + b\ln\left[\frac{S}{10} + 1\right] - c[frz]^{0.5} + 50 \qquad (17)$$

Where, in this instance:

a = -25.39;

b = -23.27;

c = -99.5;

d = 50;

The definitions of *TI*, and *S* are the same as the SHRP index (Table 4). However, the frost components, *N* and *R* are eliminated and replaced by the freezing rain component, *frz*, which is the number or days recording freezing rain (Jianzhong, 1999). Like the SHRP index, Ontario MOT's is calculated on a seasonal basis.

5.0 A SPECIFIC LOOK AT UTAH

As discussed in Section 1, Utah’s complex terrain and resulting microclimates present a significant variable to consider in the development of a severity index that will be applicable statewide. Within UDOT, one prior study was completed which compared seasonal snowfall and resource expenditures for maintenance sheds in three different geographic locations: “Measuring Efficiency of Winter Maintenance Practices” (Decker et al. 2001). The sheds included in the study were Shed 223 (Tooele), Shed 231 (West Jordan) and Shed 235 (Kimball Junction), listed in Table 12. The sheds were observed during the winter seasons of 1996/97, 1997/98 and 1998/99. The values in Table 13 show how much money each shed spent on snow and ice mitigation over the winter season and the season’s total snowfall.

The Tooele shed is more rural than West Jordan; however, West Jordan spends significantly more money on mitigation than Tooele despite having fewer lane miles and less annual snowfall (refer to Tables 12 and 13). Decker et al. does not provide insight on this contradiction, however, there are several small scale microclimatic and societal influences that may affect these results (Lynn Bernhard, UDOT Maintenance Engineer, personal communication, 2012). This example suggests that urban and rural roadway classification may add an element that should be considered in UDOT’s development of a WSI.

Though it has fewer road miles than either shed in the valley, Kimball Junction spends two to four times as much on resources due to increased storm severity, storm duration and winter season duration (Decker et al., 2001). Kimball Junction is only 20 miles to the east of the Salt Lake Valley, but it is about 2,000 feet higher in elevation. Here, geographic location and resulting differences in weather play primary roles in resource expenditure differences.

Table 12. Salt Lake City Area Sheds in Decker et al. (2001)

Shed Number	Location	Snow Climate	Lane Miles in Service
Shed 223	Tooele, UT (elev. 4900 ft.)	Salt Lake Valley	412, rural and interstate
Shed 231	West Jordan, UT (elev. 4600 ft.)	Salt Lake Valley	252, urban and interstate
Shed 235	Kimball Junction, UT (elev. 6700 ft.)	Wasatch Mountains	143, rural and interstate

Table 13. Snow Totals and Annual Expenditures from Decker et al. (2001)

		1996/1997	1997/1998	1998/1999
Tooele (223)	**Expenditures**	$294,214	$252,018	$191,497
	Snowfall (cm)	239 cm	292 cm	221 cm
West Jordan (231)	**Expenditures**	$400,944	$528,498	$525,231
	Snowfall (cm)	161 cm	165 cm	96 cm
Kimball Junction (235)	**Expenditures**	$972,639	$853,946	$788,466
	Snowfall (cm)	345 cm	354 cm	395 cm

6.0 UDOT WEATHER RESOURCES

6.1 Road Weather Information Systems

UDOT operates a network of RWIS Environmental Sensing Stations (ESS), which monitor atmospheric and road conditions along highway routes throughout the state. See Figure 3 for a map of RWIS ESS locations. Most of the RWIS ESS are located along interstates and within metro areas; however, there are also ESS located at critical mountain passes and other weather trouble spots throughout the state. UDOT's RWIS network is currently comprised of 73 weather stations, including 5 portable stations that are mounted on trailers, and more ESS are installed every year. The portable weather stations are easily deployed anywhere there is a need for temporary environmental data gathering, such as during construction or a UDOT research project. The remaining weather stations are permanently constructed on the roadside, in order to accurately gather data for nearby stretches of highway. 30 of the permanent RWIS stations are equipped with road sensors which provide pavement temperature, freezing point temperature of the liquid solution on the road surface, and road surface state: dry, wet, ice, snow, and slush. All RWIS ESS are outfitted with an air temperature and relative humidity probe, 18-inch sub-ground temperature probe, an anemometer, and most with a precipitation presence sensor and a solar radiation pyranometer. In addition to the weather instruments, each site also includes cameras, either fixed snapshot or pan-tilt-zoom streaming, the latter of which can be controlled remotely from a computer and use an infrared light for night viewing. Furthermore, UDOT manages a network of approximately 800 traffic cameras in the Wasatch Front, Park City and St. George metro areas and an additional 85 pan-tilt-zoom cameras in rural locations. This network of

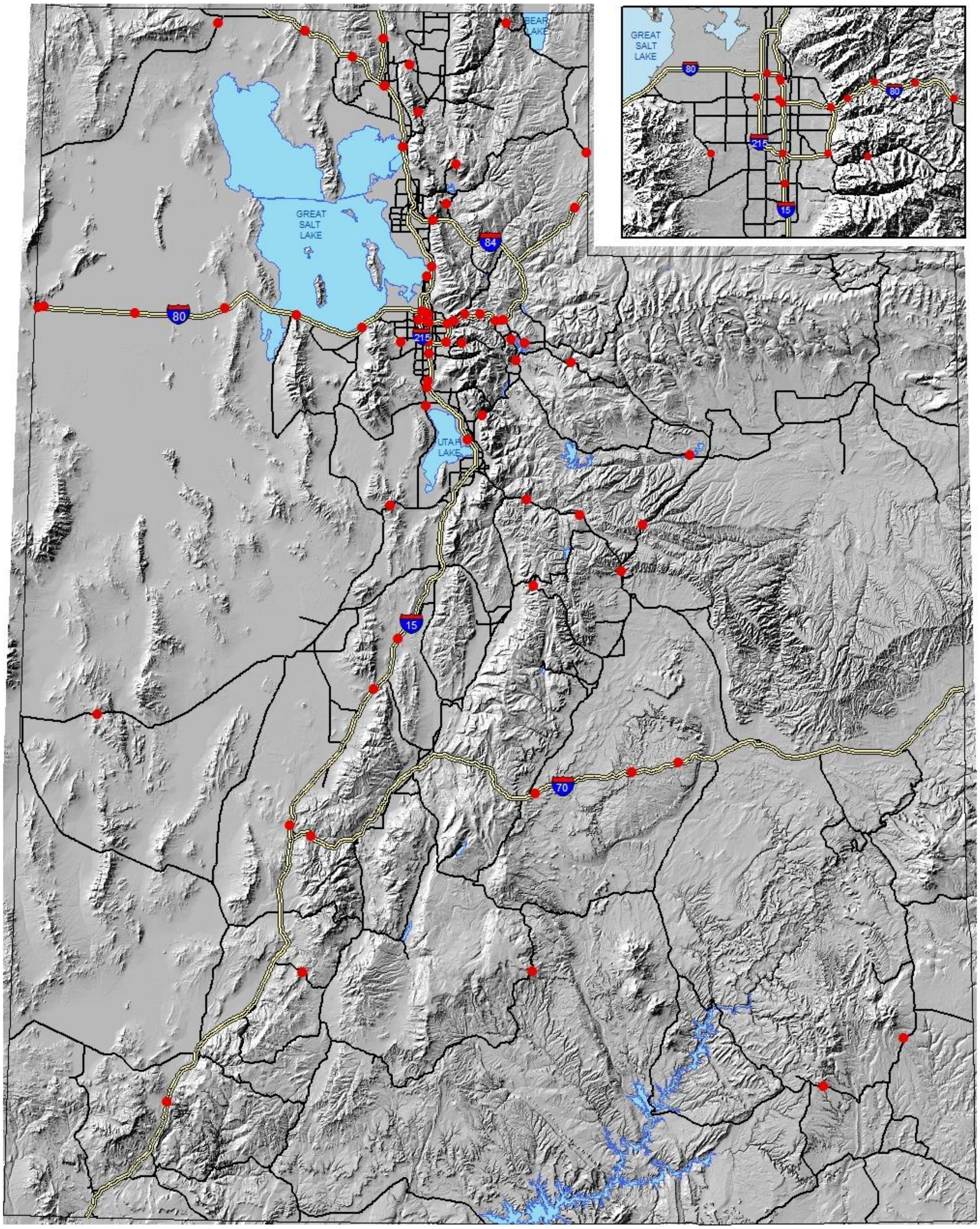

Figure 3. RWIS-ESS in Utah denoted by red dots

cameras are useful for visual observation of road weather conditions and the presence of road snow at certain locations; however, these sites lack weather data collection.

RWIS ESS are used for a number of purposes: maintenance personnel monitor RWIS data for critical road surface conditions which determine mitigation tactics; UDOT's road weather forecasters use RWIS to verify forecasts and monitor changing environmental conditions; public motorists have access to RWIS via the UDOT Traffic website and smart phone application, and they use the information to plan their travel; and archived RWIS data facilitate research projects and storm case studies.

However, because of Utah's size and variability in terrain, large data gaps are present between ESS. The formulation of a WSI in Utah will need to consider solutions to filling in the gaps in data throughout the state's complex terrain. Some solutions are discussed further in Section 7.

6.2 Radar

Radar data is used by UDOT meteorologists and field personnel for monitoring current weather conditions. However, Utah is one of the states with least radar coverage in the United States (see Figure 4). Radar locations KMTX and KICX are responsible for most of the coverage that exists in Utah. KMTX is located on Promontory Point, on the north side of the Great Salt Lake, and KICX is located in southern Utah, northeast of St. George. Several factors limit radar range: (1) The signal is emitted at a minimum angle of 0.5° above the horizon; therefore, as the beam propagates further from the site its elevation increases. (2) The curvature of Earth's surface also increases the beam's elevation away from the radar source (see Figure 5). (3) A further contributing factor is that Utah's radars are situated at high elevations, in an effort

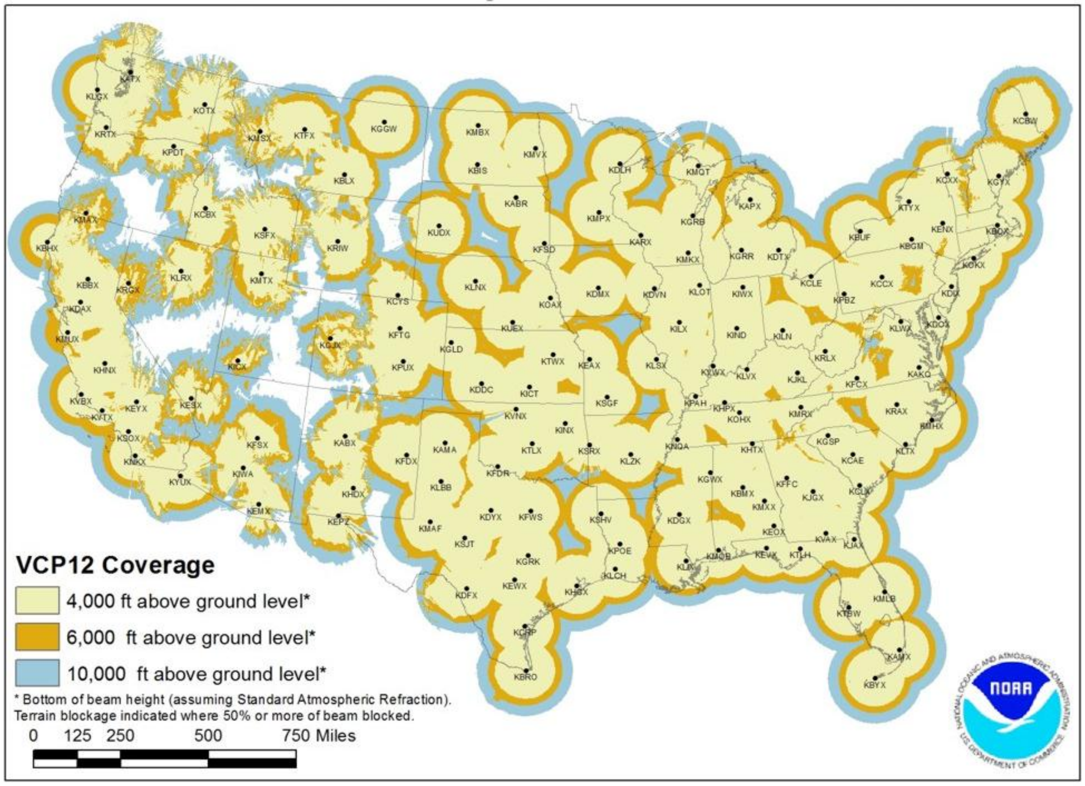

Figure 4. NEXRAD radar coverage at 4,000, 6,000 and 10,000 feet above ground level (image courtesy of the National Oceanographic and Atmospheric Administration)

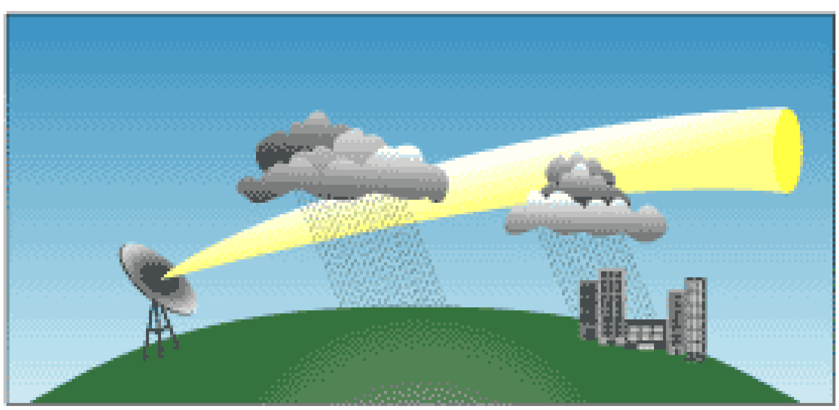

Figure 5. Earth surface curvature effect on radar signal (image courtesy of the Australian Bureau of Meteorology)

to reduce beam blockage from mountainous terrain. Because the radar beam originates from a high elevation, in combination with the former two effects, the beam reaches high altitudes quickly and frequently overshoots precipitation. When the beam overshoots precipitation, it does not show up on the radar. Overshooting is further enhanced during winter, because most of Utah's winter precipitation falls from low-elevation clouds that are less than 5,000 ft. above ground level (compare to coverage in Figure 4). Furthermore, the beam may also be blocked by high terrain surrounding the radar, blocking almost all radar data in mountainous terrain.

The effects listed here combine to greatly reduce radar areal coverage, leaving large gaps in radar data across the state. ESS properly deployed in radar-poor regions can help to fill in data gaps, but, unlike radar, ESS are only point measurements and they cannot detect precipitation upstream of a location.

7.0 FUTURE DEVELOPMENT

7.1 The Need for High Resolution Data Analysis and Forecasting

As in prior work, a WSI in Utah will be able to gather weather data as a proxy for mitigation impacts at locations statewide, and will distill the impacts into a single index value. Using the resulting value, UDOT maintenance managers will be able to compare impacts from one drastically different location to another and evaluate resource usage on a normalized scale. Utah's complex terrain necessitates high spatial resolution data gathering techniques to accomplish this goal. Moreover, previous research is noticeably lacking in methods for performing WSI calculations on a storm-by-storm basis, and this remains a primary goal going forward.

No two storm systems impact the state of Utah in the same way, and terrain-induced microclimates make for difficult comparison between locations. Microclimates and small scale variability result from 85,000 square miles of complex terrain and large bodies of water. Resolution of shaded areas, frost pockets, and bridges would be important to incorporate into the development of a severity index in Utah, and a road's elevation, aspect and vicinity to a water body are important to include for site-to-site comparison.

The canyons along the Wasatch Front provide a good example of variability within a small area, and variability of impacts between different storm types. A map of the Wasatch Front and adjacent canyons is shown in Figure 6. Storm winds coming from the southwest, for example, result in much higher precipitation totals along US-189 in Provo Canyon than would be found in adjacent canyons such as Parley's or Ogden Canyon because of the way the terrain is

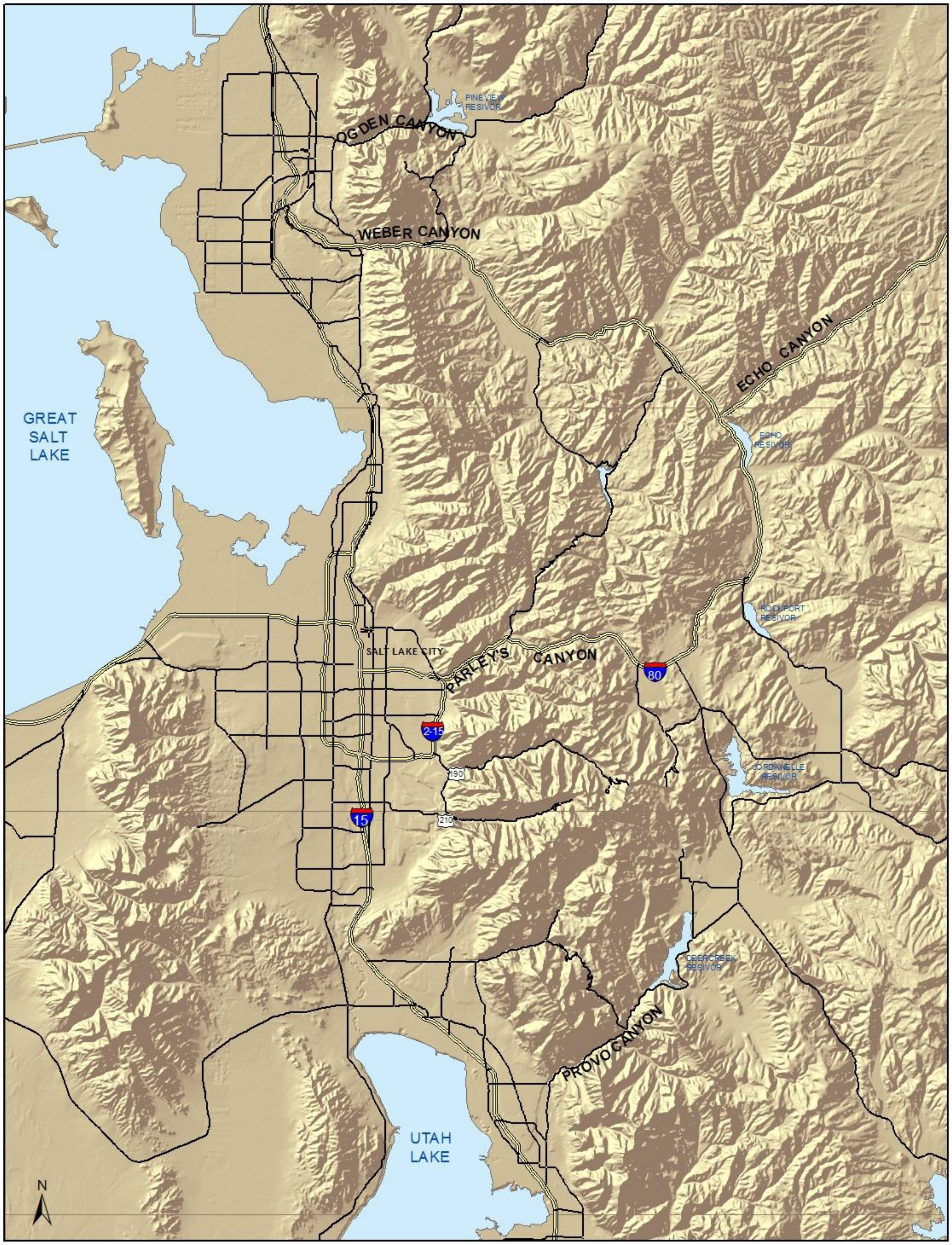

Figure 6. Map of the Wasatch Front and Back with adjacent canyons: Ogden, Weber, Parleys, Provo and others

oriented. However, storm winds coming from the northwest favor higher precipitation rates in Parleys and Ogden Canyons. Additionally, often during the winter season, lake effect snow from the Great Salt Lake may impact one location along the Wasatch Front drastically differently than another, only a few miles away. Most of the large lakes in Utah experience lake effect or enhanced snowfall, adding to weather variability across the state. Also, as previously mentioned, there is significant variability throughout a single canyon, due to areas of shading, bridges, elevation changes, etc. These are just a couple of examples that show that the weather measurement on a smaller scale must be taken into account.

In order to accomplish storm-by-storm and location-specific WSI calculations, higher resolution weather data analysis is necessary. Rather than restrict calculations to the 73 RWIS ESS across the state, advanced techniques can be employed to fill in data gaps and more accurately represent surface weather as it changes across Utah's complex topography. Mesoscale analysis systems, such as Real-Time Mesoscale Analysis (RTMA, De Pondeca, et al. 2011), combine weather observation data with numerical weather modeling to produce a high resolution analysis of the current surface weather. Computational power restricts the resolution at which data assimilation systems can run, but resolutions may be increased when run over a smaller domain. The RTMA is currently resolved to a 5-kilometer (3.1-mile), terrain-following grid over the continuous United States (De Pondeca, et al. 2011).

The Pavement Precipitation Accumulation Estimation System (PPAES) is another tool that fills in data gaps. This algorithm combines surface point precipitation observations with radar and satellite data and outputs a smoothed estimation of precipitation accumulation, even in areas with low radar coverage. Further development of PPAES is currently in progress, and its performance in areas of complex terrain and very low radar coverage is currently under review (Townsend, et al. 2011).

Mobile weather sensing also offers options to close road weather-specific data gaps across Utah. For this technique, weather sensors are attached to vehicles (plows, for example) and the data is transmitted to a central server and mapped along the driven route. With some exceptions, mobile weather sensors can measure the same atmospheric and road parameters as a stationary RWIS ESS. UDOT is currently evaluating its truck fleet for mobile sensor deployment.

The large scale approach taken in Strong et al.'s 2005 work may not be suitable for UDOT's interests, and a highly detailed winter severity index has not yet been completed for a mountainous region of the United States or Canada. Therefore, it is recommended that future development of a WSI in Utah employ a mesoscale analysis tool or mobile sensing technology for optimal accuracy and resolution. An added benefit of using high resolution analysis techniques will be improved road weather forecasting in Utah when combined with a road weather model such as METRo (Crevier and Delage, 2001). Accurate forecasts have been shown to reduce maintenance costs by millions of dollars per year (Shi, et al. 2007), and higher resolution forecasts may improve cost savings even more. In this case, UDOT forecasters may even be able to forecast the WSI before a storm hits.

7.2 Weather Parameters Specific to Utah

An initial step in creating a severity index should be cataloging weather variables that impact roads in Utah and contribute to maintenance difficulties. Because of Utah's elevation and location in the Intermountain West, its weather variables must be considered uniquely. For example, because Utah rarely, if ever, experiences freezing rain, it would be more logical to build an index that places less importance on freezing rain than some current indices, such as the SHRP index. The following are some aspects of weather in Utah that should be considered in an index:

- Snowfall rate: Determines mitigation technique (refer to tables in Appendix B).
- Road temperature: Determines mitigation technique (refer to tables in Appendix B).
- Road temperature trend: This variable becomes important when temperatures are dropping from above freezing to below freezing as precipitation is falling. Accumulation on untreated roads will likely freeze if road temperature trends continue to fall below freezing and rain falling on pavement often makes pre-treating difficult or impossible.
- Solar radiation: Solar radiation directly influences road temperature, and in complex terrain, solar angle and shading will change road temperature dramatically. Trouble spots often occur in shaded locations. A road with exposure to solar radiation will be warmer than a road in clouds or shade.

- Road frost: Road frost is a non-precipitation phenomenon. Mountain basins and lakes are areas that are likely to develop road frost. Both areas are cooler than the surrounding terrain, usually overnight, and lakes add moisture to the air. Bridge frost is also a concern, as bridges cool faster than the surrounding roadway. Frost pockets are harder to fight because their locations are more subtle and not always visible.
- Precipitation type: May encompass wet snow, dry snow, ice pellets, rain changing to snow, etc. Wet, dense snow is more difficult to plow than dry snow because it is heavier and packs down faster. This variable is primarily dependent on temperature. Colder air temperatures result in drier snowfall, where as temperatures closer to freezing or a little above freezing produce wetter, denser snowfall. As previously mentioned, when an event starts as rain and eventually changes to snow any pre-storm treatment could be washed off of the road.
- Wind speed (for blowing and drifting snow): The potential for blowing and drifting snow depends on the consistency of the snow. The snow-water equivalent (SWE) is a ratio that relates how much liquid water exists in surface snow. A low SWE ratio will blow and drift during lower wind speeds than dense, high SWE snow conditions. Generally, wind speeds greater than 20 mph will generate blowing and drifting snow of less than 15% SWE. For greater SWE ratio snow, wind speeds required for blowing and drifting increase significantly (Personal Communication, Jeff Williams, Northwest Weathernet forecaster).

A second step in assigning severity to a weather event is to weight the relative impact of the storm elements or weather variables. Mitigation difficulty is a central factor in determining how each weather variable should be weighted in relation to others. Variable weights can be determined theoretically or empirically. Qiu (2008) showed that a theoretical assignment of weighting constants can be further tuned using maintenance personnel’s perceived level of severity. Weather variable determination and weighting should be accomplished within a complex terrain framework. Utilizing aforementioned techniques in high resolution data analysis are recommended once impacting weather variables are chosen and weighted.

8.0 CONCLUSION

The severity of winter weather conditions contributes greatly to the resource consumption of a DOT. Treatment can range from plowing only to plowing while distributing over 400 lbs. /lane mile of chemical treatment for hours at a time. Observing how others have approached the concept of developing a severity index provides a foundation for UDOT's study. Many of the other studies seem to have at least one helpful feature worth taking note. "The Manual of Practice for an Effective Anti-Icing Program" (Ketcham et al., 1996) provides a vague estimate of how much snow and ice mitigation resources can be consumed under certain weather scenarios. Qiu's "Performance for Highway Winter Maintenance Operations" (2008) offers insight as to what variables should be considered and how to obtain a normalizing constant to appropriately account for each variable's impact. Meanwhile, Decker et al. (2001) and Strong et al. (2005) addressed complex topography issues. Cerruti and Decker (2011) demonstrated how to utilize and simplify data from other studies to manipulate their own WSI format. Decker et al. (2001) specifically observed three UDOT sheds in varying geographic locations and urbanization settings. Finally, whether it was modifying an existing index or creating a new one from scratch, each state DOT's methodology observed in this study offered valuable insight on how they arrived at their final indices, and the relative usefulness of each one.

However, few studies have taken a perspective that is similar, in its entirety, to the one UDOT will likely take, of a high-resolution, storm-by-storm calculation of WSI. ITD's WSI is specifically used for maintenance performance measurement. Its methodology is simplified, and would be easily repeatable for UDOT; however, UDOT's interests go beyond the basic point calculation employed by ITD. Mesoscale analysis and mobile sensing technology are reasonable tools for UDOT to employ to fill in data gaps and calculate a higher resolution WSI. Utah's many microclimates necessitate such an approach. Furthermore, the higher resolution in data will facilitate storm-by-storm analysis, which is the goal of a UDOT WSI.

It is important to consider Utah's climate on a larger scale, too. Except for Idaho, the state DOTs with existing WSIs is represented by the Midwest region. There, climate is vastly different in comparison to Utah. Because of these differences, a perspective should be taken that not only regards terrain influences, but also regards differences in the storm elements to be considered. As discussed in Section 7, there are specific weather variables that are more often present than others. Freezing rain, for example, is rarely seen in Utah, so it would not be a significant term in a Utah WSI. It is recommended that expert weather knowledge, from the forecaster to field personnel, be utilized in Phase II of this project, to assist in identifying important large scale and small scale weather variables to be identified in the severity index.

9.0 APPENDIX

9.1 Appendix A

Table 1A. Observed Winter Severity Studies

State/Author(s)	Seasonal WSI	Storm-by-Storm Index	WSI Primary Function	Comments
Qiu (2008)	No	Yes	Traffic operations and maintenance	Storm severity index that observes severity on a storm-by-storm basis. Index is used in a final traffic operation formula.
Strong et al. (2005)	Yes	No	Traffic operations	Approximates seasonal accident rates based on winter severity.
Boselly et al. (1993)	Yes	No	Maintenance	SHRP winter index. Designed to assign a seasonal winter severity score to any location without geographic discrimination.
Cerutti and Decker (2011)	No	Yes	Human intrinsic value	A local winter storm scale that basis winter severity on public perception.
Decker et al. (2001)	Yes	No	Maintenance	Uses SHRP winter index to compare expenditure between three geographically distinct UDOT maintenance sheds.
Idaho	Yes	Yes	Maintenance	Created a storm-by-storm index that takes road surface state conditions into account.
Indiana	Yes	No	Maintenance	Created their own winter index based off of criteria interest and surveying maintenance crews.
Iowa	Yes	No	Maintenance	Winter index that favors time constant. Considers duration of precipitation and snow consistency.
Kansas	Yes	No	Maintenance	Uses SHRP winter index.
Massachusetts	In Progress	No	Maintenance	WSI under development by contractor.
Minnesota	Yes	No	Maintenance	Uses SHRP winter index.
Ontario	Yes	No	Maintenance	Created a modified version of the SHRP winter index.
Wisconsin	Yes	No	Maintenance	Created a modified version of the SHRP winter index.

9.2 Appendix B

Table 1B. Weather event: Light snow storm

PAVEMENT TEMPERATURE RANGE, AND TREND	INITIAL OPERATION: pavement surface at time of initial operation	INITIAL OPERATION: maintenance action	INITIAL OPERATION: dry chemical spread rate, kg/lane-km (lb/lane-mi): liquid	INITIAL OPERATION: dry chemical spread rate, kg/lane-km (lb/lane-mi): solid or prewetted solid	SUBSEQUENT OPERATIONS: maintenance action	SUBSEQUENT OPERATIONS: dry chemical spread rate, kg/lane-km (lb/lane-mi): liquid	SUBSEQUENT OPERATIONS: dry chemical spread rate, kg/lane-km (lb/lane-mi): solid or prewetted solid	COMMENTS
Above 0°C (32°F), steady or rising	Dry, wet, slush, or light snow cover	None, see comments			None, see comments			1) Monitor pavement temperature closely for drops toward 0°C (32°F) and below 2) Treat icy patches if needed with chemical at 28 kg/lane-km (100 lb/lane-mi); plow if needed
Above 0°C (32°F), 0°C (32°F) or below is imminent;	Dry	Apply liquid or prewetted solid chemical	28 (100)	28 (100)	Plow as needed; reapply liquid or solid chemical when needed	28 (100)	28 (100)	1) Applications will need to be more frequent at lower temperatures and higher snowfall rates 2) It is not advisable to apply a liquid chemical at the indicated spread rate when the pavement
ALSO **-7 to 0°C (20 to 32°F)**, remaining in range	Wet, slush, or light snow cover	Apply liquid or solid chemical	28 (100)	28 (100)				temperature drops below -5°C (23°F) 3) Do not apply liquid chemical onto heavy snow accumulation or packed snow
-10 to -7°C (15 to 20°F), remaining in range	Dry, wet, slush, or light snow cover	Apply prewetted solid chemical		55 (200)	Plow as needed; reapply prewetted solid chemical when needed		55 (200)	If sufficient moisture is present, solid chemical without prewetting can be applied
Below -10°C (15°F), steady or falling	Dry or light snow cover	Plow as needed			Plow as needed			1) It is not recommended that chemicals be applied in this temperature range 2) Abrasives can be applied to enhance traction

Notes

CHEMICAL APPLICATIONS. (1) Time initial and subsequent chemical applications to *prevent* deteriorating conditions or development of packed and bonded snow. (2) Apply chemical ahead of traffic rush periods occurring during storm.

PLOWING. If needed, *plow before chemical applications* so that excess snow, slush, or ice is removed and pavement is wet, slushy, or lightly snow covered when treated.

Table 2B. Weather event: Light snow with period(s) of moderate or heavy snow

PAVEMENT	INITIAL OPERATION				SUBSEQUENT OPERATIONS					COMMENTS
TEMPERATURE RANGE, AND TREND	pavement surface at time of initial operation	maintenance action	dry chemical spread rate, kg/lane-km (lb/lane-mi)		maintenance action	dry chemical spread rate, kg/lane-km (lb/lane-mi)				
			liquid	solid or prewetted solid		liquid		solid or prewetted solid		
						light snow	heavier snow	light snow	heavier snow	
Above 0°C (32°F), steady or rising	Dry, wet, slush, or light snow cover	None, see comments			None, see comments					1) Monitor pavement temperature closely for drops toward 0°C (32°F) and below 2) Treat icy patches if needed with chemical at 28 kg/lane-km (100 lb/lane-mi); plow if needed
Above 0°C (32°F), 0°C (32°F) or below is imminent;	Dry	Apply liquid or prewetted solid chemical	28 (100)	28 (100)	Plow as needed; reapply liquid or solid chemical when needed	28 (100)	55 (200)	28 (100)	55 (200)	1) Applications will need to be more frequent at lower temperatures and higher snowfall rates 2) Do not apply liquid chemical onto heavy snow accumulation or packed snow 3) After heavier snow periods and during light snow fall, reduce chemical rate to 28 kg/lane-km (100 lb/lane-mi); continue to plow and apply chemicals as needed
ALSO **-4 to 0°C (25 to 32°F),** remaining in range	Wet, slush, or light snow cover	Apply liquid or solid chemical	28 (100)	28 (100)						
-10 to -4°C (15 to 25°F), remaining in range	Dry, wet, slush, or light snow cover	Apply prewetted solid chemical		55 (200)	Plow as needed; reapply prewetted solid chemical when needed			55 (200)	70 (250)	1) If sufficient moisture is present, solid chemical without prewetting can be applied 2) Reduce chemical rate to 55 kg/lane-km (200 lb/lane-mi) after heavier snow periods and during light snow fall; continue to plow and apply chemicals as needed
Below -10°C (15°F), steady or falling	Dry or light snow cover	Plow as needed			Plow as needed					1) It is not recommended that chemicals be applied in this temperature range 2) Abrasives can be applied to enhance traction

Notes

CHEMICAL APPLICATIONS. (1) Time initial and subsequent chemical applications to *prevent* deteriorating conditions or development of packed and bonded snow. (2) *Anticipate increases in snowfall intensity. Apply higher rate treatments prior to or at the beginning of heavier snowfall periods to prevent development of packed and bonded snow.* (3) Apply chemical ahead of traffic rush periods occurring during storm.

PLOWING. If needed, *plow before chemical applications* so that excess snow, slush, or ice is removed and pavement is wet, slushy, or lightly snow covered when treated.

Table 3B. Weather event: Moderate or heavy snow storm

PAVEMENT	INITIAL OPERATION				SUBSEQUENT OPERATIONS			COMMENTS
TEMPERATURE RANGE, AND TREND	pavement surface at time of initial operation	maintenance action	dry chemical spread rate, kg/lane-km (lb/lane-mi)		maintenance action	dry chemical spread rate, kg/lane-km (lb/lane-mi)		
			liquid	solid or prewetted solid		liquid	solid or prewetted solid	
Above 0°C (32°F), steady or rising	Dry, wet, slush, or light snow cover	None, see comments			None, see comments			1) Monitor pavement temperature closely for drops toward 0°C (32°F) and below 2) Treat icy patches if needed with chemical at 28 kg/lane-km (100 lb/lane-mi); plow if needed
Above 0°C (32°F), 0°C (32°F) or below is imminent;	Dry	Apply liquid or prewetted solid chemical	28 (100)	28 (100)	Plow accumulation and reapply liquid or solid chemical as needed	28 (100)	28 (100)	1) If the desired plowing/treatment frequency cannot be maintained, the spread rate can be increased to 55 kg/lane-km (200 lb/lane-mi) to accommodate longer operational cycles 2) Do not apply liquid chemical onto heavy snow accumulation or packed snow
ALSO **-1 to 0°C (30 to 32°F),** remaining in range	Wet, slush, or light snow cover	Apply liquid or solid chemical	28 (100)	28 (100)				
-4 to -1°C (25 to 30°F), remaining in range	Dry	Apply liquid or prewetted solid chemical	55 (200)	42-55 (150-200)	Plow accumulation and reapply liquid or solid chemical as needed	55 (200)	55 (200)	1) If the desired plowing/treatment frequency cannot be maintained, the spread rate can be increased to 110 kg/lane-km (400 lb/lane-mi) to accommodate longer operational cycles 2) Do not apply liquid chemical onto heavy snow accumulation or packed snow
	Wet, slush, or light snow cover	Apply liquid or solid chemical	55 (200)	42-55 (150-200)				
-10 to -4°C (15 to 25°F), remaining in range	Dry, wet, slush, or light snow cover	Apply prewetted solid chemical		55 (200)	Plow accumulation and reapply prewetted solid chemical as needed		70 (250)	1) If the desired plowing/treatment frequency cannot be maintained, the spread rate can be increased to 140 kg/lane-km (500 lb/lane-mi) to accommodate longer operational cycles 2) If sufficient moisture is present, solid chemical without prewetting can be applied
Below -10°C (15°F), steady or falling	Dry or light snow cover	Plow as needed			Plow accumulation as needed			1) It is not recommended that chemicals be applied in this temperature range 2) Abrasives can be applied to enhance traction

Notes

CHEMICAL APPLICATIONS. (1) Time initial and subsequent chemical applications to *prevent* deteriorating conditions or development of packed and bonded snow -- *timing and frequency of subsequent applications will be determined primarily by plowing requirements*. (2) Apply chemical ahead of traffic rush periods occurring during storm.

PLOWING. *Plow before chemical applications* so that excess snow, slush, or ice is removed and pavement is wet, slushy, or lightly snow covered when treated.

Table 4B. Weather event: Frost or black ice

PAVEMENT TEMPERATURE RANGE, TREND, AND RELATION TO DEW POINT	TRAFFIC CONDITION	INITIAL OPERATION maintenance action	INITIAL OPERATION dry chemical spread rate, kg/lane-km (lb/lane-mi) liquid	INITIAL OPERATION dry chemical spread rate, kg/lane-km (lb/lane-mi) solid or prewetted solid	SUBSEQUENT OPERATIONS maintenance action	SUBSEQUENT OPERATIONS dry chemical spread rate, kg/lane-km (lb/lane-mi) liquid	SUBSEQUENT OPERATIONS dry chemical spread rate, kg/lane-km (lb/lane-mi) solid or prewetted solid	COMMENTS
Above 0°C (32°F), steady or rising	Any level	None, see comments			None, see comments			Monitor pavement temperature closely; begin treatment if temperature starts to fall to 0°C (32°F) or below and is at or below dew point
-2 to 2°C (28 to 35°F), remaining in range or falling to 0°C (32°F) or below, *and* equal to or below dew point	Traffic rate less than 100 vehicles per h	Apply prewetted solid chemical		7-18 (25-65)	Reapply prewetted solid chemical as needed		7-18 (25-65)	1) Monitor pavement closely; if pavement becomes wet or if thin ice forms, reapply chemical at higher indicated rate 2) Do not apply liquid chemical on ice so thick that the pavement can not be seen
	Traffic rate greater than 100 vehicles per h	Apply liquid or prewetted solid chemical	7-18 (25-65)	7-18 (25-65)	Reapply liquid or prewetted solid chemical as needed	11-32 (40-115)	7-18 (25-65)	
-7 to -2°C (20 to 28°F), remaining in range, *and* equal to or below dew point	Any level	Apply liquid or prewetted solid chemical	18-36 (65-130)	18-36 (65-130)	Reapply liquid or prewetted solid chemical when needed	18-36 (65-130)	18-36 (65-130)	1) Monitor pavement closely; if thin ice forms, reapply chemical at higher indicated rate 2) Applications will need to be more frequent at higher levels of condensation; if traffic volumes are not enough to disperse condensation, it may be necessary to increase frequency 3) It is not advisable to apply a liquid chemical at the indicated spread rate when the pavement temperature drops below -5°C (23°F)
-10 to -7°C (15 to 20°F), remaining in range, *and* equal to or below dew point	Any level	Apply prewetted solid chemical		36-55 (130-200)	Reapply prewetted solid chemical when needed		36-55 (130-200)	1) Monitor pavement closely; if thin ice forms, reapply chemical at higher indicated rate 2) Applications will need to be more frequent at higher levels of condensation; if traffic volumes are not enough to disperse condensation, it may be necessary to increase frequency
Below -10°C (15°F), steady or falling	Any level	Apply abrasives			Apply abrasives as needed			It is not recommended that chemicals be applied in this temperature range

Notes

TIMING. (1) Conduct initial operation in advance of freezing. Apply liquid chemical up to 3 h in advance. Use longer advance times in this range to effect drying when traffic volume is low. Apply prewetted solid 1 to 2 h in advance. (2) In the absence of precipitation, liquid chemical at 21 kg/lane-km (75 lb/lane-mi) has been successful in preventing bridge deck icing when placed up to 4 days before freezing on higher volume roads and 7 days before on lower volume roads.

Table 5B: Weather event: Sleet storm.

PAVEMENT TEMPERATURE RANGE, AND TREND	INITIAL OPERATION maintenance action	INITIAL OPERATION chemical spread rate, kg/lane-km (lb/lane-mi)	SUBSEQUENT OPERATIONS maintenance action	SUBSEQUENT OPERATIONS chemical spread rate, kg/lane-km (lb/lane-mi)	COMMENTS
Above 0°C (32°F), steady or rising	None, see comments		None, see comments		1) Monitor pavement temperature closely for drops toward 0°C (32°F) and below 2) Treat icy patches if needed with prewetted solid chemical at 35 kg/lane-km (125 lb/lane-mi)
Above 0°C (32°F), 0°C (32°F) or below is imminent	Apply prewetted solid chemical	35 (125)	Plow as needed, reapply prewetted solid chemical when needed	35 (125)	Monitor pavement temperature and precipitation closely
-2 to 0°C (28 to 32°F), remaining in range	Apply prewetted solid chemical	35-90 (125-325)	Plow as needed, reapply prewetted solid chemical when needed	35-90 (125-325)	1) Monitor pavement temperature and precipitation closely 2) Increase spread rate toward *higher indicated rate* with increase in sleet intensity 3) Decrease spread rate toward *lower indicated rate* with decrease in sleet intensity
-10 to -2°C (15 to 28°F), remaining in range	Apply prewetted solid chemical	70-110 (250-400)	Plow as needed, reapply prewetted solid chemical when needed	70-110 (250-400)	1) Monitor precipitation closely 2) Increase spread rate toward *higher indicated rate* with decrease in pavement temperature or increase in sleet intensity 3) Decrease spread rate toward *lower indicated rate* with increase in pavement temperature or decrease in sleet intensity
Below -10°C (15°F), steady or falling	Plow as needed		Plow as needed		1) It is not recommended that chemicals be applied in this temperature range 2) Abrasives can be applied to enhance traction

Notes

CHEMICAL APPLICATIONS. (1) Time initial and subsequent chemical applications to *prevent* the sleet from bonding to the pavement. (2) Apply chemical ahead of traffic rush periods occurring during storm.

9.3 Appendix C

Oregon Mountains:

$$AccRate = 1.56324 - 0.02219T_{min} - 0.01734W_{avg} + 6.1992S_{avg} - 0.2208F \quad (1C)$$

Oregon Valleys:

$$AccRate = 1.70484 - 0.03049T_{min} - 0.01719W_{avg} + 1.61371S_{fr} \quad (2C)$$

Oregon Plains:

$$AccRate = 0.62354 - 0.0038T_{max} - 1.14164S_{freq} + 3.38151T_{<fre} \quad (3C)$$

California Mountains:

$$AccRate = 0.68288 + 0.03969F \quad (4C)$$

California Valleys:

$$AccRate = 0.77838 - 0.00318T_{min} + 0.03792N_{sno} \quad (5C)$$

California Plains:

$$AccRate = 1.02545 - 0.0061T_{min} + 0.01502N_{sno} \quad (6C)$$

9.4 Appendix D

South Bend Region:

$$WI = -5.98483 * Frost + 13.73518 * Freezing\_Rain + 12.57288 * Drifiting - 25.18103 * Snow + 28.78145 * Snow\_Depth + 4.29121 * Hour + 6.77877 Avg\_Temp \quad (1D)$$

Fort Wayne Region:

$$WI = 7.05832 * Frost - 16.21024 * Freezing\_Rain + 6.31394 * Drifting + 31.24970 * Snow + 25.36240 * Snow\_Depth + 1.23828 * Hour - 6.95440 * Avg\_Temp \quad (2D)$$

Indianapolis Region:

$$WI = 3.42152 * Frost + 7.96888 * Freezing\_Rain + 7.24260 * Drifting - 14.044284 * Snow + 16.63333 * Snow\_Depth + 1.50251 * Hour - 3.90486 * Avg\_temp \quad (3D)$$

Evansville Region:

$$WI = 0.01116 * Frost + 23.68383 * Freezing\_Rain + 43.46891 * Drifting - 18.77938 * Snow + 63.02214 * Snow\_Depth + 0.23399 * Hour - 0.32291 * Avg\_Temp \tag{4D}$$

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